Spectral Response of the Southern Ocean Surface Circulation to Wind

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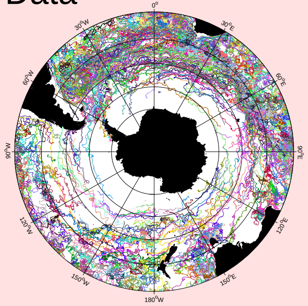
1. Introduction

The surface circulation south of 30°S is investigated by using the drifter-derived velocity measurements from the WOCE Surface Velocity Program (SVP). The objective of this study is to quantify and understand how the surface circulation is related to local wind forcing.

For this study, Holey-sock drifters are used. These consist of a drogue centered at 15 m linked to a surface buoy which transmits its position via the ARGOS satellite tracking system.

NCEP/NCAR and ECMWF 10-m wind fields are used to investigate the relationship between the surface circulation and the wind forcing. Along 40-day drifter trajectories, wind velocities are interpolated to form a time series $\mathbf{W}$ contemporaneous to the drifter-derived velocity time series $\mathbf{U}_{drifter}$. These temporal time series are analyzed using spectral and coherence techniques that allow the motions to be decomposed and studied as a function of frequency.

2. Data



From November 1989 to December 2001, 1407 independent drifter trajectories south of 30°S are available, giving position and drifter-derived velocities every six hours [*Hansen and Poulain, 1996*].

NCEP and ECMWF 6-hourly gridded 10-m winds were interpolated onto the drifter positions (1.125° grid for NCEP, 1.875° grid for ECMWF). Each trajectory was divided when possible into an integer number of 40-day long time series to obtain 5709 (NCEP) or 5680 (ECMWF) time series.

3. Methods

spectral analysis:
For either ocean or current velocity vector $\mathbf{V}$, the normalized spectrum is:

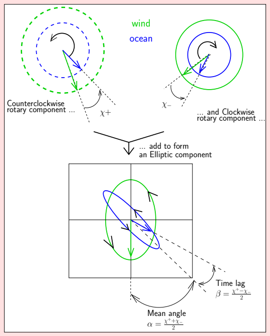
$$S(f) = \left\langle \tilde{\mathbf{V}}\tilde{\mathbf{V}}^* \right\rangle / f_r,$$

where $\tilde{.}$ designates the Fourier transform and $\langle . \rangle$ the ensemble average. $f_r = 1/40$ cpd is the frequency resolution for this study.

cross-spectral analysis:
The *coherence squared* γ^2 and the *coherence phase* χ between the ocean velocity $\mathbf{U}_d$ and the wind velocity $\mathbf{W}$ are:

$$\gamma^2(f) = \frac{\left|\left\langle \tilde{\mathbf{U}}_d \tilde{\mathbf{W}}^* \right\rangle\right|^2}{\left\langle \tilde{\mathbf{U}}_d \tilde{\mathbf{U}}_d^* \right\rangle \left\langle \tilde{\mathbf{W}} \tilde{\mathbf{W}}^* \right\rangle}, \quad \chi(f) = \arctan\left[\frac{\mathcal{I}\left(\left\langle \tilde{\mathbf{U}}_d \tilde{\mathbf{W}}^* \right\rangle\right)}{\mathcal{R}\left(\left\langle \tilde{\mathbf{U}}_d \tilde{\mathbf{W}}^* \right\rangle\right)}\right].$$

► In rotary spectral analysis, positive frequencies correspond to counterclockwise (anticyclonic) motions and negative frequencies to clockwise (cyclonic) motions. The two types of motions add and form an ellipse in each frequency band.
► Between the wind and ocean ellipses, a spatial phase (or mean angle) α and a temporal phase (or lag) β is computed. See sketch to the right.



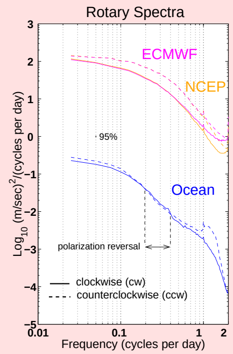
4. Complete Dataset

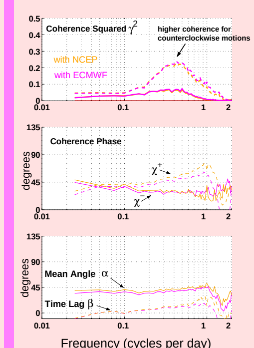
spectra similarities:

► Ocean and wind spectra both decrease with frequency. This is more dramatic for the ocean (3 decades) than for the wind (2 decades).
► A small but statistically significant diurnal peak in all spectra is seen.

. . . and dissimilarities:

► Wind spectra exhibit a clear counterclockwise (anticyclonic) polarization over the complete frequency range.
► The ocean spectrum shows the same polarization but not for frequencies between 0.2 and 0.4 cpd.



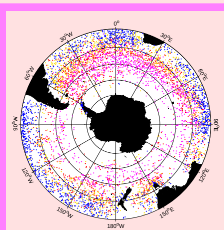


► The **coherence squared** between winds and surface currents is low but above the 95% confidence level.
► ECMWF winds are slightly more coherent with the currents than NCEP.
► Coherence peaks for both oppositely rotating motions in the 0.4 to 0.5 cpd bands.
► For all frequency bands, the coherence is higher for anticyclonic co-rotating motions than cyclonic, especially in the peak bands.

► A constant positive sign for the **coherence phase** means here that the ocean velocity vector is directed to the *left* of the wind velocity vector in agreement with Ekman's theory.
► The ccw phase χ^+ is generally greater than the cw phase χ_-.

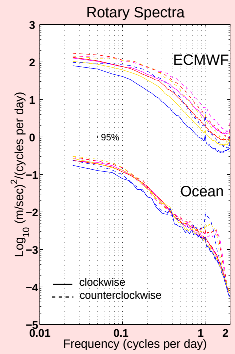
► The **mean angle** between the wind and ocean ellipses is fairly constant over the frequency range 0.025-1 cpd: 42.97° ± 3.60° for NCEP and 39.51° ± 3.50° for ECMWF.

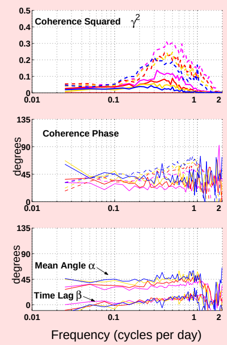
5. Wind Speed Sorting



40-day averaged wind speed is used to sort the data into 4 groups of intensifying wind speed: blue (weakest), yellow, red and magenta (strongest). The map above shows the drifters median positions for each time series with a color corresponding to their group.

► Unlike the wind spectra, ocean spectra do not exhibit strong energy level differences between the four groups.
► In the inertial band (1 to 2 cpd), peaks indicate the latitudinal bias for each data group.



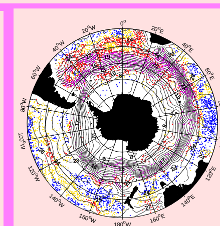


► The **coherence squared** increases with wind speed. Higher levels are still found in the 0.4 to 0.5 cpd bands.
► On average over the 0.025-0.1 cpd frequency range:

	χ^+	χ^-	α	β
blue	54.25	35.96	45.10	9.14
yellow	48.77	32.33	40.55	8.22
red	49.28	30.83	40.05	9.22
magenta	44.02	25.78	34.90	9.12

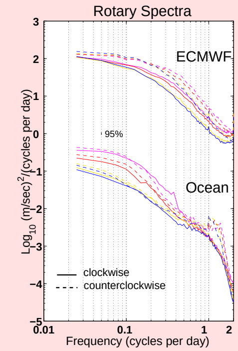
► χ^+, χ^- and α decrease substantially with wind speed, i.e **the ocean current vector is closer to the wind vector for higher wind speed**.

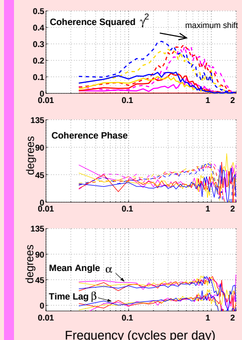
6. Geostrophic Sorting



Historical hydrographic data from *Gouretski and Jancke, 1998* are used to compute geostrophic velocities at the surface in order to sort the data into 4 groups of intensifying background geostrophic velocities: blue (weakest), yellow, red and magenta (strongest).
The map above shows dynamic height (in dm) relative to 3000m and the drifter median positions for each time series with a color corresponding to their group.

► Ocean spectra are distinct at low frequencies, wind spectra at high frequencies.





► The maximum **coherence squared** shifts from 0.225 cpd (4.4 day period motions) to 0.475 cpd (2.1 day) as background geostrophic speed increases.
► On average over the 0.025-0.1 cpd frequency range:

	χ^+	χ^-	α	β
blue	48.17	28.00	38.08	10.08
yellow	53.64	32.72	43.18	10.46
red	51.70	32.55	42.13	9.57
magenta	48.70	30.21	39.46	9.24

► Only small phase variations from one group to another are seen.

7. What does this tell us about the surface circulation?

The model we are looking at is:

$$\mathbf{U}_{drifter} = \mathbf{U}_{surface} + \mathbf{N} + \mathbf{U}_{slip}$$

► $\mathbf{U}_{surface} = (a_r + i \times a_i)\ \mathbf{W}$: linear response of the surface circulation to wind

► $\mathbf{N}$: noise (geostrophic currents, mesoscale eddies, instrumental . . .)

► $\mathbf{U}_{slip} = s\ \mathbf{W}$: wind slip, see box about it.

in that case:

$$\gamma^2(f) = \frac{1}{1 + \frac{\left\langle \tilde{\mathbf{N}}\tilde{\mathbf{N}}^* \right\rangle}{[(a_r+s)^2 + a_i^2]\left\langle \tilde{\mathbf{W}}\tilde{\mathbf{W}}^* \right\rangle}},$$

$$\chi^{\pm}(f) = \arctan\left[\frac{a_i}{a_r + s}\right].$$

What is seen in the results?

► The surface circulation in the Southern Ocean is most coherent with the wind in the 0.4-0.5 cpd bands. **Anticyclonic motions are much more coherent than cyclonic motions**.
► The spatial phase α is on average 42.97° ± 3.60° for NCEP and 39.51° ± 3.50° for ECMWF in the 0.025-1 cpd frequency range.

What makes us think this is a sensible model?

► Wind speed sorting shows that **more energy in the wind** causes higher coherence.
► Geostrophic sorting show that noise spectral distribution influences the coherence but not the mean angle.

What is left to understand?

► Why is the ocean response strongly polarized?
► What makes the coherent part of the Southern Ocean motions to respond with different α but constant α as a function of wind energy?
► How should we distinguish the wind slip from the ocean surface circulation?

Wind Slip

► Drifter-derived ocean surface velocities are usually corrected for the direct action of the wind on the drifter's surface buoy [*Niiler et al., 1995*]:

$$\mathbf{U}_{corrected} = \mathbf{U}_{drifter} - s\mathbf{W}$$

with $s \times 10^2 = 4.63/40 \pm 1.03/40$ for SVP drifters for winds up to 10 m s^{-1}.
► Wind slip causes an erroneous additional downwind component of ≈ 1.15 cm s^{-1} in 10 m s^{-1} winds.
► The results presented are without wind slip correction.

References

Gouretski, V. V. and K. Jancke, 1998. A new climatology for the world ocean. WHP SAC Tech. Rep. no. 3, woce report no. 162/98, WOCE Special Analysis Centre, Max-Planck Institute, Hamburg.

Hansen, D. V. and Pierre-Marie Poulain, 1996. Quality Control and Interpolations of WOCE-TOGA Drifter Data. *JPO*, **13**, 900–909.

Niiler, P. P., A. L. Sybrandy, K. Bi, P. Poulain, and D. Bitterman, 1995. Measurements of the water-following capability of holey-sock and TRISTAR drifters. *DSR*, **42**, 1951–1964.

Drifters data provided by Peter Niiler of SIO.

NCEP winds provided by NOAA-CIRES Climate Diagnostics Center. ECMWF winds provided by the Data Support Section of the Scientific Computing Division at NCAR.

For further information and handouts see http://plum.ucsd.edu/elipot/main.html.